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Communication Scheme for Loosely Coupled Mobile User Groups in Wireless Sensor Fields

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***Abstract*—We propose a communication mechanism to support mobility of loosely coupled mobile users in sensor applications with multiple sources. First, we examine problems for mobility support of the loosely coupled users in wireless sensor networks with multiple source nodes, and then study the dynamic sink communication model to support a mobile user with sink-oriented tree based data gathering from multiple sources and data-centric unicasting. Finally, we present an energy-efficient solution to support the loosely coupled mobile users through single data-gathering tree establishment with a distributed manner and the gathering tree based data-centric multicasting.**

***Index Terms*—loosely coupled user groups, group mobility, communication model, multicast**

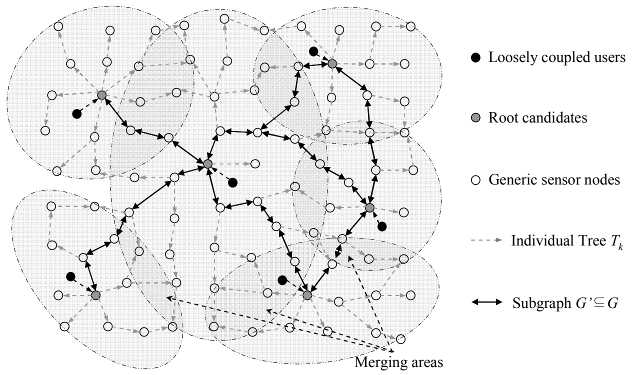

Figure 1. Tree constructions from $\exists k \in K$: a set of mobile users

I. INTRODUCTION

Typical communication architecture of wireless sensor networks consists of users, sinks, and sensor nodes [1]. In many sensor applications, the users, such as firefighters and soldiers, tend to move around sensor fields and derive interested information on their mission [2]. Moreover, they may be grouped according to major missions, e.g. fire-extinguishing and saving victims, and the user groups may be interested in equivalent information about each mission. The groups of mobile users could be classified into two categories according to existence of direct communication channels among the mobile users: tightly coupled mobile user group and loosely coupled mobile user group.

The tightly coupled user group means that there are direct communication channels among all mobile users. Namely, every user can communicate with others via legacy networks or be existed in radio range of others by collective movement. Thus, the tightly coupled mobile users might be able to easily negotiate with each other to query only once about same information in order to prevent redundant global querying from all users. Also, sharing data-gathering structure to collect data from all sources in interested sensor field might be easily constructed by direct negotiation, and collected data may be easily shared if the data is delivered to any user.

Contrastively, in case of the loosely coupled mobile user group, a wireless sensor network is only communication channel among the mobile users. So, when the loosely coupled group queries equivalent information and constructs a network structure, negotiation among all users via the wireless sensor network should be required. Also, the mobile users should communicate with each other via only the sensor networks to share collecting data. Such information obtainment routine of the loosely coupled group may require high communication cost, and thus the properties would cause reduction of network lifetime. Hence, a communication mechanism for supporting the loosely coupled mobile users should be energy-efficiently designed with considering reduction of communication costs for the negotiations and the collected data sharing via the wireless sensor network.

Communication mechanisms have already been proposed to support mobility of the loosely coupled mobile users [3~7]. However, the mechanisms may have several problems in terms of supporting sensor applications with multiple sources, such as monitoring mean temperature and detecting all victims over disasters areas. First, mechanisms proposed in [3~5] can not gather and aggregate sensed data from multiple sources. This is because they construct a source-oriented network structure per each source to solve global querying from mobile users. Thus, if large numbers of sources are existed, too many network structures could be constructed and such constructing overhead might lead to reduction of network lifetime. Second problem is high communication cost for information sharing. To data delivery from multiple sources to loosely coupled mobile users, a mechanism proposed in [6, 7] exploits unicast manner from

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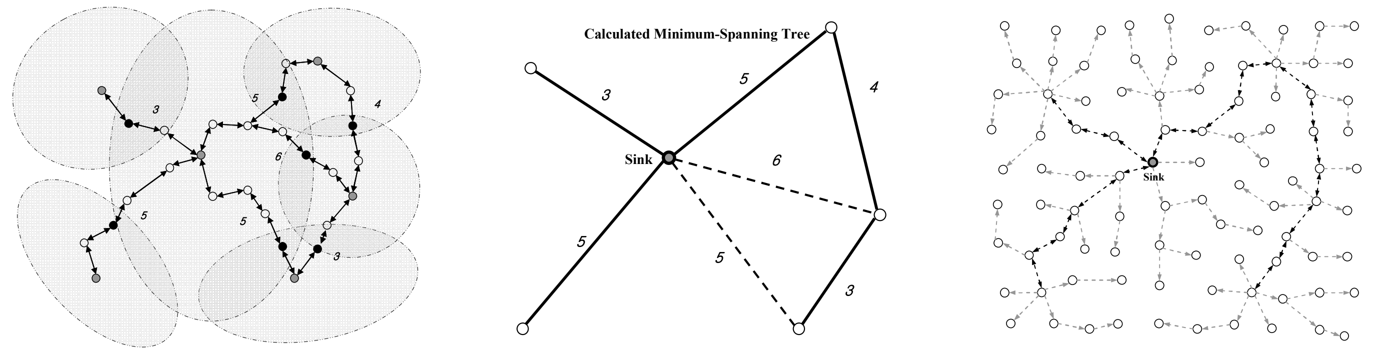


(a) Path organization among V' as E' (b) Minimum-spanning tree from graph $G'(V', E')$ (c) Merged single data-gathering tree

Figure 2. Distributed single data-gathering tree establishment

each source to each user. The unicasting of all data may cause energy exhaustion of sensor nodes on delivery paths.

In [8], a communication model based on a sink-oriented structure has been proposed to offer mobility to a mobile user and data gathering from multiple sources in a sensor network, named the *dynamic sink model*. In this model, a user temporarily selects a near sensor node as a sink. The user then queries interested information to collect data from the multiple sources. The collected data would deliver to the user by data-centric unicasting mechanism. However, although this model considers a sink-oriented structure to collect data from many sources, the model could establish many network structures in proportion to the number of mobile users. In other words, querying and data collecting would be performed per each user about same information. Thus, loosely coupled user group mobility support by the dynamic sink model might cause excessive energy consumption of whole sensor nodes. Also, data unicasting from each sink to each mobile user might require high communication costs.

Consequently, to support mobility of loosely coupled users in the wireless sensor network with multiple sources, the communication mechanism should consider constructing single network structure, which all mobile users in a group share, to gather data from the multiple sources with aggregation [11] and delivering collected data via multicast manners to mobile users. In this paper, we propose a novel communication solution to energy-efficiently support mobility of loosely coupled mobile user groups in sensor applications with multiple sources. The solution consists of a distributed single data-gathering tree establishment scheme through merging trees from each user without preceding query negotiation among users and a data-centric multicasting scheme based on the single data-gathering tree structure.

II. System Model and Assumptions

The core of the proposed solution is mapping between a data-gathering tree and a mobile user group. The user group appoints a temporarily selected sink and constructs the data-gathering tree by query flooding. The selected sink, i.e. root of the tree, collects data from multiple sources with aggregation, and then the sink forwards collected information to multiple mobile users of the group via multicasting.

The basic design of the proposed solution is based on the following assumptions:

- A large number of homogeneous sensor nodes are evenly and densely scattered over a vast field, and then they self-organize a multi-hop ad hoc network.
- Mobile users could be frequently interested in equivalent or similar information on the sensor field since the sensors are deployed for a specific goal over a targeted field.
- Mobile users have globally unique identifier values and the users can assign session identifier about the same information with lifetime to check querying time.
- Every sensor node could be temporarily selected and function as a sink during lifetime of a query and the sensor has locally a unique address as a local identifier.
- Every user can generate a message with same format for the equivalent information so that every sensor node can check whether queries from different users are same or not.

III. Distributed Data Gathering Tree Establishment

A. Tree Construction Attempts from Each Mobile User

The wireless sensor network may be modeled as a graph $G = (V, E)$, where V is the set of sensor nodes, and E is the set of directed wireless links. The tree T_k from each user k is the subgraph of G; S_k denotes a root candidate selected from k and it is root of T_k; and N_k denotes the set of sensor nodes that participates in T_k. Then, $V_k = \{S_k, N_k\}$ and $V = \cup V_k$, $\{\exists k \in K$: a mobile user set of a loosely coupled group$\}$.

To form tree T_k from $k \in K$, k selects the nearest node as S_k and propagates a query message, which contains *Interest Task Description*, *Session_ID*, *Session_Lifetime*, and *User_ID*, interested information.

1) If the node S_k does not receive same query message yet

The S_k then saves the query and transfers the query to the sensor network through flooding. While the query flooding is fulfilled, every sensor node saves and maintains the query messages with local address of previous node as a parent node in a *query table*. When each sensor $a \in N_k$ deals with the query to flooding, we also consider level of *an* in T_k to construct the T_k as round shape tree. Namely, level of S_k is 0 and node a_i is located in level i (i = 1, 2, … , n). If a node a_i in level i receives same query compared by *User_ID* and *Session_ID*, which are used to check whether the query is same information request in time from same user, from a lower level node than i – 1, a_i changes parent and own level, and re-transmits the query. Namely, level i means hop distances from the root of T_k, i.e. the root candidate S_k, to level i nodes.

This query transmission would be performed until the query is disseminated to a sensor node that has already received one and more queries from other users, or to edge nodes of the wireless sensor network. Figure 1 shows tree constructions from $\exists k \in K$. The sensors in the merging areas might receive one and more queries from different users. So, they could have one and more levels from different root candidates.

2) If the node S_k has already received same query message

At the S_k selection step, if the selected node has already received a query message about same information from another $k' \in K$, i.e. the *Interest Task Description* of saved query from k' is same with the *Interest Task Description* of query from k and *Session_Lifetime* is available, the S_k becomes a generic sensor node which is belong to $T_{k'}$ of itself. The node then registers the query from k to the $S_{k'}$ of the $T_{k'}$ to renew *Session_Lifetime* to *Session_Lifetime* of query from k. The $S_{k'}$ uses the renewed *Session_Lifetime* in next subsections to construct the single data-gathering tree.

3) If the single data-gathering tree has been constructed

If the single data-gathering tree has already been constructed globally and *Session_Lifetime* of previous query is available, the selected node S_k becomes to a agent node of the mobile user k to delivery collected information from the root of the single data-gathering tree to k. The agent node requests collected information to the root of the global single tree and maintains a relaying path to the k. In section V, the collected information delivery routine is addressed in detail.

B. Path Organization among Root Candidates

As shown in figure 1, the sensor nodes in the merging areas, denoted reporting nodes, are attached to one and more trees rooted from different root candidates. In other words, the reporting nodes are located at different levels from the different trees. To organize paths among root candidates, the reporting nodes report a *path organizing message* to the candidate that has lowest level counts. The message contains a *Interest Task Description* addressing the interested information, all *User_ID* obtained from all received queries about the information, local addresses of all root candidates belong to *User_ID*, all lastly renewed *Session_Lifetime* values belong to *User_ID*, and all level values belong to *User_ID*. When the messages are delivered from each reporting node to selected root candidate, every node on the delivering paths saves and maintains the local address of the previous node that forwarded the message during given time, which might be set by application operators before scatting sensor nodes.

If a root candidate receives the path organizing messages from the reporting nodes, the candidate chooses first one and ignore other reporting to select shortest path from a reporting node to the candidate. The chosen message then is analyzed to calculate hop distances from the candidate to others in the message. Also, the highest value of *Session_Lifetime* values in the message, i.e. the newest one, is selected to effectively maintain the global single tree. *User_ID* and local address of other candidates would be used to select the root node of the global single tree in final subsection. These analyzed results saved and maintained into a *neighbor root candidate list table* with *User_ID* indexing.

The candidate then retransmits the first path organization message to the saved previous node about the first message. The previous node also forwards the message to own previous node. Namely, the message is forwarding via the reported path until the reporting node which generated the message. If the reporting node receives the message again, the node reports the message to all other candidates through backward paths of query flooding. The nodes on the backward paths also save and maintain own previous node. If other candidates receive the message, they also analyze the message and organize own neighbor root candidate list table. Such path organization message exchange would be performed until every root candidates know relationship among them.

Each time new merging area is generated; this reporting routine may be performed between related two root candidates. Moreover, if a candidate receives new reporting, the candidate should report value of the new reporting to all other candidates in own candidate list table. So, all candidates can know communication paths among the all candidates and hop distances of the paths. Consequently, weighted connected undirected graph $G'(V', E') \subseteq G$, where V' is the set of root candidates and E' is the set of communication paths could be organized by the reporting routine. Figure 2 (a) shows this subgraph G'.

C. Minimum-Spanning Tree Construction among Candidates

The minimum spanning tree over the G' could be organized according to Kruskals's algorithm [12] which is one popular algorithm. The algorithm requires that all the edges E' should be ordered before beginning to build the spanning tree. This sorting and calculating are performed in each root candidates by exploiting *User_ID* and hop distances of the own neighbor root candidate list table. After this calculating by the algorithm, all candidates can generate same single minimum-spanning tree in distributed manner. Figure 2 (b) shows calculated the minimum-spanning tree on the G'.

Table I. Pseudo code to calculating the minimum-spanning tree

```
calculateMinimumSpanningTree (weighed connected undirected graph G')
    tree = null;
    edge = sequence of all edges of graph G' sorted by weight;
    for (i = 1; i <= | E'| and |tree| < | V'| - 1; i++)
        if (e_i from edge dose not form a cycle with edge in tree)
            add e_i to tree;
```

D. Root Selection and Merged Single Tree Establishment

In this step, single root candidate is selected among all candidates as the root of the calculated minimum-spanning tree. To establish the optimized single data-gathering tree, we consider two conditions for selecting the root. First, among the set of the root candidates *V'*, a candidate or candidates which have most numbers of edges is/are selected. Second, if one and more candidates are selected by first condition, a candidate of them which has the largest hop distance value edge is selected as the root. Once more, if one and more candidates have same hop distance value as the largest value edge, a candidate of the lowest *User_ID* number may be selected finally. The selected candidate, i.e. the temporary sink, becomes the root of merged single data gathering tree, and other candidates might be general branches. Every root candidate finds out the root of the spanning tree of itself. All candidates then register own parent candidate on the minimum-spanning tree as a child branch through previously organized path among root candidates. Figure 2 (c) shows the finally established single data-gathering tree.

IV. Data-Centric Information Multicasting

If the root of the single data-gathering tree, i.e. temporary sink, collects data from all sources with the data aggregation like a technique [11], the sink should forwards the aggregated information to all mobile users in a loosely coupled group, who queried the information, by multicasting.

A. Agent Node Selection and Information Request

In the proposed multicast scheme, a mobile user in a loosely coupled group selects a sensor in radio range as an agent node to request interested and collected information. The user then sends *information request message* via the agent node to the root of the single data-gathering tree which is constructed by querying about the interested information. Since the agent node has already been attached to the tree, the agent has known local address of a parent node on the tree.

The information request message contains *Dest_Addr*, *Src_Addr*, *User_ID*, and *Requesting Information Description*. *Dest_Addr* and *Src_Addr* mean local address of the parent node on the tree and own local address respectively. The *User_ID* is the identifier of the request user. The *Requesting Information Description* addresses the interested and collected information and is exactly same with of the *Interest Task Description* of the query message. When the information request message is forwarded from the agent node to the root, a sensor node on the requesting path, i.e. a backward path from the agent node to the root on the tree, checks whether *Dest_Addr* indicates own local address. If two address are matched, the node saves *Src_Addr*, *User_ID*, and *Requesting Information Description* in the receive message to a *requesting history table*. The node also searches local address of own parent about the information by matching *Interest Task Descriptions* of saved queries in the query table and the *Requesting Information Description*. The node then changes *Dest_Addr* and *Src_Addr* of the information request message to the local address of the searched parent node and own local address respectively.

For forwarding of the information request message, if a node that has already received and saved the message from a mobile user repetitiously receives the message from other mobile users, the node additionally saves all *User_ID*s and all *Src_Addr*s in previous history of the requesting history table. Then, the node discards the all redundant request messages.

B. Information Multicasting from a Sink to All Agent Nodes

Once the information request messages are arrived at the root, the root merely replies collected information to neighbor nodes that sent the messages. After the neighbor nodes are received, the nodes check which *Requesting Information Description* in the requesting history table is matched to the information. The neighbor nodes then transmit the information to all local addresses in the matched list of the table by one hop multicasting. Every node that has a local address of the all local addresses also performs the checking and retransmitting operations. The information forwarding by the checking and retransmitting operations is fulfilled until the information is arrived at agent nodes.

C. Information Relaying from Agent Nodes to Mobile Users

To support localized mobility of mobile users during the requesting time, if a user changes its position and outs of its agent node's radio range, which means that the agent node cannot receive beacon signal from the user, the agent searches neighborhoods that receive the beacon signal and then selects one of them as a relay node and saves its address. If the user moves again and deviates from the relay node's radio range during a moment also, the first relay node searches next relay node again from its neighborhood nodes which now receive beacon signals from the user.

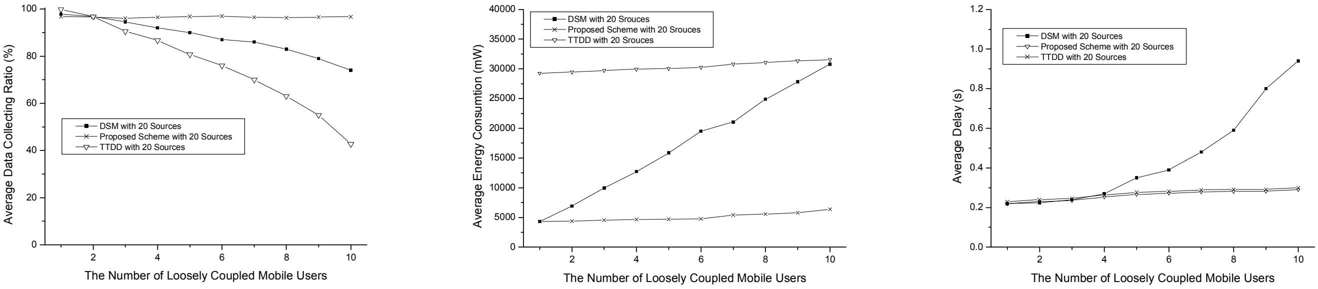
This relay nodes selection routine is performed until the user receives requested information. If the user does not receive the information during a moment, the user should re-selects an agent node and re-requests to the root.

V. Performance Evaluation

In this section, we present and describe metrics and simulation environments to evaluate performance of the proposed communication scheme. Our goals in conducting this evaluation study are three-fold. First, we would like to prove that the proposed scheme is able to support mobility of loosely coupled users with better performances than related work, TTDD [5] and the dynamic sink model [8]. Second, we also would like to show that our multicasting is more energy-efficient and faster than unicasting [6, 8].

A. Simulation Environments and Metrics

We simulate the proposed scheme on QualNet simulator [9]. Table II describes the detailed setup for our simulation. A sensor node's transmitting, receiving, and idling power consumption rates are 21mW, 15mW and 0.03mW respectively.



(a) Average data collecting ratio (b) Average energy consumption (c) Average delay

Figure 3. Comparing about Information Collecting and Sharing

TABLE II. Simulation environment setting

Parameters	Values
Simulation network space	500m x 500m
The number of nodes	100 nodes
Node placement	Uniform deployment
Transmission range	Uniform 55m
User mobility model	Random way point
User speed	10 m/s
The number of users	1~10 and 1~20

The device parameters are mostly chosen in reference the MICA specification [10]. We choose four metrics to analyze the performance of the proposed scheme and to compare it to the related work:

Average data collecting ratio measures the ratio of the number of successfully received reports at a sink to the total number of reports generated by sensor nodes. Due to incomplete data aggregation, this metric computes the average arrival rate of data generated by all leaf nodes and some intermediate nodes at the sink.

Average Energy Consumption is defined as an average of the total communication energy the network consumes; the idle state energy is not counted because it related to the data generation interval and does not indicate the efficiency of data delivery. If the value of the metric is 0, it means that overall sensor nodes do not consume their energy any more, that is, the system lifetime of a sensor network is over.

Average Delay measures the average latency between the all moment source nodes deployed uniformly on sensor field send a packet back to a sink and the moment a user receives an information packet that the sink gathers and send. In the case of TTDD, delivery time from the sink to the user is counted as value 0 since TTDD defines the sink is same the user.

Average Information Delivery is defined as the ratio of the number of successfully received reports at a user to the number originally sent by the sink.

B. Simulation Results

We first compare the proposed scheme to support loosely coupled mobile users with other mechanisms, TTDD and the Dynamic Sink Model (DSM). We then compare the data-centric multicast scheme with the unicast schemes, EEDD and USHER in the DSM.

1) Comparing about Information Collecting and Sharing

We compare the proposed scheme with TTDD and DSM related to the number of users with 20 sources. The mobile users request interested information to sensor field in time order. TTDD thus constructs 20 source-based grid structures. In case of DSM, each mobile user establishes a data-gathering tree in proportion to the number of mobile users.

Figure 3(b) shows the average energy consumption when the number of mobile users changes. TTDD and the proposed scheme almost maintain the total energy consumption of energy consumption to one mobile user although the number of the users is increased. However, DSM rapidly increase in the total energy consumption in proportion to the number of the users since each user appoints a dynamic sink, makes a data-gathering tree, and collects data from all sensor nodes. On the other hand, the proposed scheme are that single sink makes a data-gathering tree, collects data from all sensor nodes, and forwards the data to multiple mobile users. Accordingly, the proposed scheme increases only the energy consumption that each mobile user forwards its user registration message and receives the aggregated information from the sink although the number of mobile users increases.

In addition, the proposed scheme shows very lower total energy consumption than TTDD about five times. This is because TTDD constructs the source-based grid structure to disseminate data per each source. Thus, in this simulation, TTDD constructs 20 grid structures. Such excessive structure construction leads to sudden reduction of network lifetime.

Figure 3(a) shows the average data collecting ratio related to the number of mobile users. For the data collecting, TTDD consumes too much energy to construct 20 grid structures and users requests in time order so that data collecting ratio TTDD rapidly decreases in proportion to the number of users. This is because sudden reduction of network lifetime and collision by the too many structure construction. Also, DSM also globally constructs data-gathering trees in proportion to the number of users. So, battery power of whole sensor nodes might be suddenly reduced. This battery exhaustion causes decrease of the average information collecting ratio. Also, the many trees by DSM might induce collision when data collecting and

(a) Average information delay

(b) Average energy consumption

Figure 4. Comparing about Information Delivery Manners

information delivery. In case of the proposed scheme, only one network structure to gather interest information is established though the number of users is increased. Thus, the average information collecting ratio is maintained almost 100%.

Figure 3(c) shows the average delay related to the number of mobile users. In TTDD, a sink is defined as a user so that delay from a sink to a user is 0. Namely, in case of TTDD, the average delay is obtained from only delivery latency from sources to sinks. Moreover, TTDD exploits multicasting scheme to disseminate data from a source to all sinks. Thus, although the number of users is increased, average delay of TTDD is almost same. The proposed scheme also uses multicasting scheme to deliver collected information and constructs only one data-gathering tree. So, the proposed scheme also maintains same performance in terms of the average delay. However, many trees of DSM increase in the collision probability for information delivery and exploit unicasting to disseminate the information. These properties rapidly increase the average delay in proportion to the number of mobile users.

2) Comparing about Information Delivery Manners

We compare the proposed multicast schemes with the unicast schemes, EEDD and USHER, related to the number of mobile users. Figure 4(a) and Figure 4(b) show the average information delay and the average energy consumption respectively. As shown in figure 4(a), the proposed multicast scheme delivers the aggregated information faster than the unicast scheme. This is due to the fact that the unicast scheme sends the data as the number of destination nodes as to forward the data to all destination nodes whereas the tree based multicast scheme sends only once the data to forward the data to all destination nodes. However, despite EEDD also exploits unicasting, EEDD shows almost same performance with the proposed multicasting in terms of the average delay. This is because EEDD provides data delivery via shortest path from all sources to all mobile users.

As shown in figure 4(b), the proposed multicast scheme consumes very less energy than the unicast schemes. The proposed multicasting excludes redundant information requests and redundant information deliveries on shared paths. So, after five users are existed, the proposed multicast scheme maintains almost same performance in terms of the average energy consumption.

VI. CONCLUSION

To support mobility of loosely coupled user groups, we take two considerable schemes into account. First scheme is single data gathering tree construction to be shared by loosely coupled mobile users. The shared tree could be established through two steps: 1) non-overlapped tree constructions from each user and 2) merging the trees into minimum spanning tree to organize single data gathering tree. This tree constructing and merging is fulfilled in distributed manners to exclude signaling among mobile users of loosely coupled group. Also, we propose a multicasting based on the shared tree to propagate collected information to multiple users of the loosely coupled group to reduce communication costs.

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